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# Evaluation of the thermal resilience of buildings in overheating in present and climate change scenarios

## *Avaliação da resiliência térmica de edificações em sobreaquecimento nos cenários presente e de alterações climáticas*

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## Abstract

Thermal resilience refers to a building's capacity to adapt to extreme thermal variations, maintaining a healthy environment for its occupants. This study aims to assess the thermal resilience of a naturally ventilated low-income residential building in overheating conditions within a region of savannah tropical climate. Various indices, including adaptive thermal comfort, Indoor Overheating Degree (IOD) and Exceedance Hours (HE), Heat Index (HI), and Standard Effective Temperature (SET) were calculated in current and climate change scenarios using two models, a standard building (HISp) and a building that incorporates passive bioclimatic strategies (HISe). It was demonstrated that thermal insulation and low absorption strategies significantly contribute to indoor environmental quality, reducing the risk of overheating exposure in all evaluated scenarios. Despite reducing discomfort hours and critical thermal stress levels, the idealized strategies do not provide adequate habitability conditions for the occupants. Overheating will become even more severe in projected future scenarios. Among the two dwellings, HISe demonstrates a superior potential to mitigate the risk of overheating compared to HISp in all the scenarios evaluated.

**Keywords:** Thermal resilience. Overheating. Tropical Savanna climate.

## Resumo

*A resiliência térmica se refere à capacidade de um edifício de se adaptar às variações térmicas extremas, mantendo um ambiente saudável para seus ocupantes. Este estudo visa avaliar a resiliência térmica de uma edificação residencial de baixa renda, naturalmente ventilada, em situação de sobreaquecimento, localizada em região climática tropical de savana. Vários índices, incluindo conforto térmico adaptativo, Grau de Sobreaquecimento Interior (IOD) e Horas Excedentes (HE), Índice de Calor (HI) e Temperatura Efetiva Padrão (SET) foram calculados, no presente e cenários futuros de mudança climática, utilizando-se dois modelos, uma edificação padrão (HISp) e uma edificação que incorpora estratégias bioclimáticas passivas (HISe). Evidenciou-se que as estratégias de isolamento térmico e baixa absorção contribuíram significativamente para a qualidade ambiental interior, reduzindo os riscos de exposição ao sobreaquecimento. Apesar de reduzir as horas de desconforto e os níveis mais críticos de estresse térmico, as estratégias idealizadas não promovem condições adequadas de habitabilidade aos seus ocupantes. O sobrequecimento se tornará ainda mais severo nos cenários futuros projetados. Entre as habitações, a HISe demonstra um potencial superior ao da HISp para mitigar o risco de sobreaquecimento em todos os cenários avaliados.*

***Palavras-chave:*** *Resiliência térmica. Sobreaquecimento. Clima tropical de savana.*

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## Introduction

A house is a place where individuals find protection from wind, rain, cold, heat, insects, and other potential natural hazards, preserving their physical and mental well-being. Having adequate housing is fundamental for their quality of life and for ensuring contentment in daily living.

According to the United Nations (United Nations, 2014), adequate housing must respect several key principles such as ownership security, affordability (related to maintenance), habitability (which covers aspects related to health, thermal comfort, structural integrity, among others), location, accessibility, cultural suitability, and the provision of essential services, materials, facilities, and infrastructure. In terms of habitability, there is a strong correlation between the concept of adequate housing and the necessity to promote comfort and well-being for the occupants. In this context, comfort can be interpreted as the absence of tension or stress, or as a state characterized by comfort, well-being, security, and tranquility.

Implementing passive bioclimatic strategies can enhance the thermal comfort of occupants in the built environment and influence their perception of temperature, which directly correlates with the effort that the thermoregulatory system requires to adapt.

Although access to adequate housing is considered a right established in the Brazilian Constitution (Brasil, 1988) and a fundamental principle in international treaties (Nações Unidas, 1948), Brazil faces a housing deficit of approximately 6 million units (FJP, 2022). Additionally, there are 24 million inadequate homes, characterized by deficiencies such as urban infrastructure, water supply, sewage, electricity, and rubbish collection, as well as issues like insufficient rooms for bedrooms, absence of bathrooms, inadequate roofing or flooring, among others (FJP, 2021).

The current Brazilian housing program MCMV ("Minha Casa Minha Vida" in Portuguese) aims to assist 2 million families by 2026. This initiative distributes financial benefits across various income brackets, mainly benefiting low-income families, as outlined by the federal government (CAIXA, 2024). The data reveal a significant increase in social housing built in recent years in Brazil, indicating ongoing efforts to reduce the housing deficit in the country, with more dwellings to be built in the next years.

In 2009, Caixa Econômica Federal, the primary financing bank for housing construction, published a standard floor plan as an example to be adopted under the MCMV program. This model was widely implemented, leading to the widespread construction of this architectural typology across Brazil. Approximately 57% of MCMV developments in Brazil consist of single-family homes, with a single-story detached dwelling as the most built construction typology, including the midwestern region, focus of this study. Regarding construction materials, the most common materials used in single-family units are concrete structures with a ceramic block (41%), followed by molded concrete walls (39%), concrete blocks (18%), and other materials (2%) (Brasil, 2015; Ortiz; Bavaresco, 2023).

Several studies indicate problems regarding the quality of social housing, that raise from the necessity of constructing a maximum number of dwellings with a limited investment, often resulting in inferior construction quality and low thermal performance (Canavarros, 2016; Montes, 2016; Triana; Lamberts; Sassi, 2016; Veiga *et al.*, 2020).

Regarding the tropical savanna climate, issues associated to thermal performance are exacerbated due to the high temperatures registered all over the year, reinforcing concerns about the adequacy of dwellings to the climate and the thermal resilience of the built environment (Apolonio; Callejas; Roseta, 2023; Callejas *et al.*, 2020, 2021; Guarda; Durante; Callejas, 2018; Guarda *et al.*, 2019a, 2020b; Jorge *et al.*, 2018).

Although there are regulations in Brazil for the thermal performance of low-income housing, such as NBR 15575 (ABNT, 2021), compliance with this standard aims to ensure a minimum level of quality and performance. However, this minimum requirement may not be sufficient to guarantee habitability and high thermal comfort levels for its occupants. Obtaining an energy efficiency label through Inmetro Normative Instruction for the Energy Efficiency Classification of Residential Buildings (INI-R), established by the Brazilian Labelling Program PBE Edifica (Brasil, 2022), or certifications for sustainable constructions, such as BREEAM (Building Research Establishment Environmental Assessment), LEED (Leadership in Energy and Environmental Design), and WELL, enables achieving higher levels of energy efficiency and thermal comfort, as they require performance exceeding the minimum quality standards. Despite progress in thermal performance standards and energy efficiency regulations in Brazil, it is observed that even the most efficient buildings, with an "A" rating, may experience periods of overheating. The primary focus of regulations and standards remains the energy performance of buildings, disregarding the thermal comfort of occupants and the risk of exposure to overheating (Guarda; Mizgier; Hernandez, 2023). Therefore, overheating and thermal resilience remain inadequately addressed in these standards, with no definition of maximum permissible limits for overheating risk in Brazil, which are not considered in neither the present scenario nor in projected future climate change scenarios. Thus, this is a research area to be explored, not only in Brazil but globally, as evidenced by recent literature (Attia *et al*., 2022; Gnecco *et al*., 2022; Guarda; Mizgier; Hernandez, 2023; Hong *et al*., 2023).

In this context, the study aims to evaluate the impact of passive bioclimatic design strategies on the thermal resilience of low-income housing situated in a tropical savanna climate region, with the city of Cuiabá/MT, Brazil, serving as the geographical reference location. To quantify thermal resilience, various indices were applied. The applicability of these indices to the tropical savanna climate is also assessed.

# Theoretical framework

## Thermal resilience and overheating in buildings

The term resilience is used in psychology, ecology, economics, and engineering, and it presents different meanings and interpretations over time, as extensively discussed by several authors (Attia *et al*., 2021; Tavakoli *et al*., 2022). In general, it is widely accepted that the term resilience refers to the capability of individuals, communities, and systems to maintain their stability and continue functioning when facing changes, challenges, and disruptions. Resilience relates to vulnerability to disturbances and the capacity to adapt and recover from shocks and events. Numerous studies have extensively examined the health and environmental implications of elevated temperatures resulting from overheating during extreme events. Exposure to overheating poses a significant threat to the population, leading to increased mortality rates attributed to cardiovascular, cerebrovascular, and respiratory diseases. Urban populations are particularly vulnerable to the effects of high temperatures, exacerbated by various factors, such as socioeconomic disparities, age, income, social status, education level, health conditions, and housing type, the latter being the primary focus of this study (Arsad *et al*., 2022).

Certain built environment characteristics present a higher risk to the health of the population, including higher housing density, building form and density, vegetation suppression, urban land use patterns, and housing typologies. Considering housing typologies and characteristics, factors such as the number of rooms, insufficient thermal insulation, inadequate natural ventilation, and limited access to equipment like fans and air conditioners contribute to an increased vulnerability to overheating risks (Arsad *et al*., 2022; Garcia-Herrera *et al*., 2010; Nayak *et al*., 2018).

Addressing the interconnection between resilience and vulnerability from the building perspective, Attia *et al*. (2021) state that a resilient building should be designed based on a vulnerability analysis that considers present and predicted future climate scenarios. This analysis will contribute to preparing both the systems and the occupants of the building to adapt for future conditions. Thermal resilience refers to the capacity of a building or system to prepare, resist, recover quickly, and adapt to major disruptions due to extreme weather conditions such as, for example, heatwaves. Temperatures worldwide continue to rise, as well as the frequency and intensity of heatwaves. Therefore, this issue becomes even more relevant, especially concerning the well-being and thermal safety of the users. Lomas and Ji (2009) suggest that resilience to climate change, susceptibility to internal heat gains, and the impact of future heat waves should be an integral part of any new construction design or building renovation. According to Burman, Kimpian and Mumovic (2014), the manifestation of the resilience concept in the built environment is directly related to overheating.

In this context, exposure to high temperatures in the built environment can lead to thermal discomfort, overheating, and, consequently, high levels of heat stress. For these reasons, reducing the high temperatures inside buildings is one of the major challenges that architecture is facing today. It is predicted that, due to climate change, the urban heat island effect and heat waves will be more intense and more frequent.

Understanding the difference between thermal comfort and heat stress is essential, considering that thermal resilience is related to both. Thermal comfort is defined as contentment with the thermal environment, marked by the absence of discomfort or stress, while heat stress refers to the physiological strain experienced when exposed to extreme temperatures, whether cold or hot.

Overheating and thermal resilience have been extensively discussed in international literature. Studies cover various regions and climates, including European countries, the United States, Canada (Amaripadath *et al*., 2023; Attia *et al*., 2023; Attia; Gobin, 2020; Hamdy *et al*., 2017; Laouadi *et al*., 2023; Laouadi; Bartko; Lacasse, 2020; Rahif; Amaripadath; Attia, 2021; Sun *et al*., 2021), as well as several other countries (Flores-

Larsen; Filippín, 2021; Flores-Larsen; Filippín; Bre, 2023; Gamero-Salinas *et al*., 2021), including Brazil (Apolonio; Callejas; Roseta, 2023; Gnecco *et al*., 2022; Guarda, 2023; Guarda; Mizgier; Hernandez, 2023).

Tavakoli *et al*. (2022) emphasized the necessity of adopting a multi-criteria approach to quantify thermal resilience. Most studies mainly focus on two resilience criteria: vulnerability (risk of overheating) and resistance (potential of passive measures to enhance thermal conditions and mitigate overheating events). Rahif *et al.* (2022) analyzed overheating assessment methods in residential building codes across European countries, identifying that user adaptation is neglected in most standards. The authors recommend incorporating short-term (hourly, daily, and weekly) and long-term (monthly and yearly) intervals in resilience evaluations to prevent overheating during heatwaves and ensure comfort throughout the year. Hendel, Azos-Diaz and Tremeac (2017) also addressed the importance of occupant behavior in reducing the negative impacts of heatwaves on health.

Some studies emphasize the interconnection between energy efficiency and thermal resilience (Baniassadi; Heusinger; Sailor, 2018; Hatvani-Kovacs *et al*., 2017; Laouadi; Bartko; Lacasse, 2021), indicating that efficiency should be considered not only for energy savings and reducing greenhouse gas emissions but also for its impact on a building's thermal resilience against extreme weather events (Sun; Specian; Hong, 2020). Several studies address occupants' vulnerability during power outage events, highlighting the interconnection between thermal resilience and passive survivability, and discussing some metrics to quantify thermal resilience (Amada *et al*., 2022; Attia *et al*., 2021; Baniassadi *et al*., 2019; Kim *et al*., 2022).

The advancements in thermal resilience classification are noteworthy. Homaei and Hamdy (2021), and Ji *et al*. (2023) proposed methods to classify a building's thermal resilience, ranging from F (the least resilient) to A+ (the most resilient), similar to the energy efficiency labeling already integrated into some building regulations. New indicators of thermal resilience, including Indoor Overheating Degree (IOD), Ambient Warmness Degree (AWD), and Overheating Escalation Factor (αIOD/AWD), have been recently developed and have been adopted in recent studies (Borghero *et al*., 2023; Flores-Larsen; Filippín; Bre, 2023; Gamero-Salinas *et al*., 2021; Rahif *et al*., 2021). These metrics, among others, are also outlined in the technical report Annex 80 published by the International Energy Agency in Buildings and Communities (IEA EBC) (INTERNATIONAL…, 2023; Levinson *et al*., 2023), which is a very important publication in the field of thermal resilience.

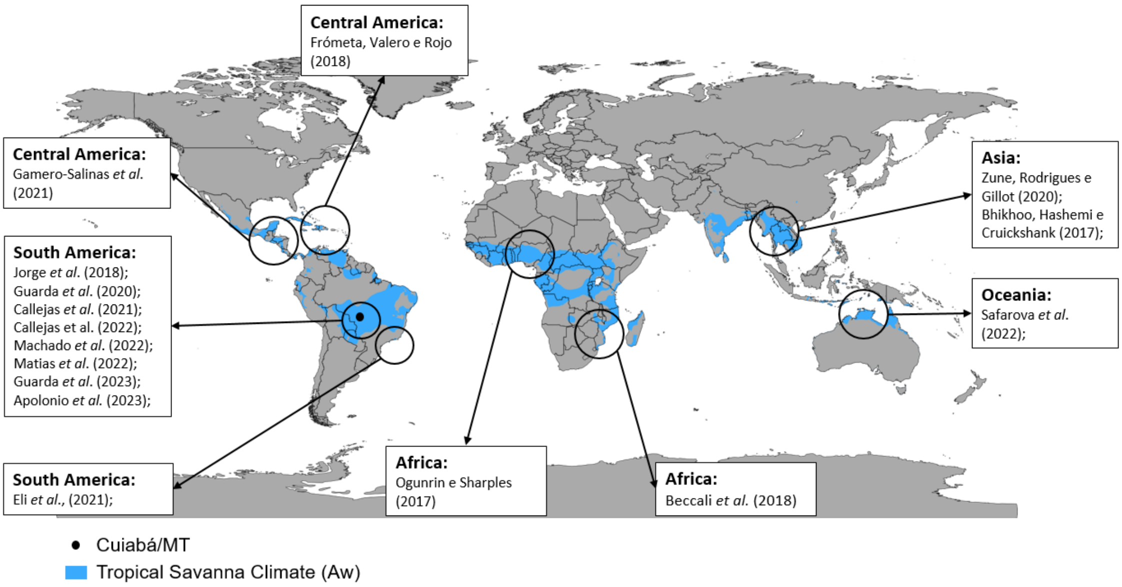
## Overheating risk evaluation in savannah tropical climate

Brazilian standards and regulations, such as NBR 15575 and the RTQ-R, are adopted in the analysis of overheating risk and thermal resilience in the tropical savannah climate region (Figure 1) (Callejas *et al*., 2021; Guarda; Durante; Callejas, 2022; Guarda *et al*., 2020b), alongside international standards, including CIBSE TM52 (Bhikhoo; Hashemi; Cruickshank, 2017), EN 15251 (Beccali *et al*., 2018; Matias *et al*., 2022), CIBSE Guide A (Zune; Rodrigues; Gillott, 2020), ASHRAE 55 (Safarova *et al*., 2022), SET temperature (Guarda; Mizgier; Hernandez, 2023), Heat Index and Humidex (Apolonio; Callejas; Roseta, 2023) and the IOD thermal resilience metric (Gamero-Salinas *et al*., 2021).

Concerning passive design measures to mitigate overheating risk, one of the most widely adopted and effective strategies is to incorporate thermal insulation in external walls and roofs, as evidenced in various studies (Bhikhoo; Hashemi; Cruickshank, 2017; Frómeta; Valero; Rojo, 2019; Guarda *et al*., 2019a, 2019b; Jorge *et al*., 2018). Other strategies include reducing thermal absorptance (Callejas; Guarda; Durante, 2023; Gamero-Salinas *et al*., 2021; Jorge *et al*., 2018), incorporating thermal mass with earth bermed walls (Callejas *et al*., 2020, 2021; Guarda *et al*., 2020a), shading, solar orientation and other measures (Beccali *et al*., 2018; Eli *et al*., 2021; Zune; Rodrigues; Gillott, 2020). It is worth noting that natural ventilation should be cautiously and selectively adopted during certain periods of the year due to high outdoor temperatures. Additionally, despite its overall positive impact, thermal insulation should be carefully implemented, as excessive insulation levels can impair performance in tropical climates (Guarda; Durante; Callejas, 2018).

The performance of low-income housing requires improvement even in the current climate (Guarda; Durante; Callejas, 2018; Jorge *et al*., 2018; Machado *et al*., 2022). Gamero-Salinas *et al*. (2021) state that achieving thermal comfort solely through passive strategies is challenging in regions with high exterior temperatures, thus, additional efforts are required to enhance the resilience of dwellings to climate change.

Figure 1 – **Studies in overheating and thermal resilience in the savannah climate region**




**Source**: adapted from Peel, Finlayson and Mcmahon (2007).

## Thermal resilience indices for buildings

The primary indices identified in the literature for assessing thermal comfort, thermal stress, and thermal resilience in buildings are presented in this section, with an emphasis on the indices that will be used to calculate overheating in this study.

The Standard 55 (ASHRAE, 2017), which allows adaptive comfort evaluation, has been the most frequently applied standard in literature to assess comfort and overheating. Indices, such as the Heat Index (HI), Humidex, and Wet-bulb Globe Temperature (WBGT), have been extensively considered as parameters to evaluate thermal stress conditions within buildings, and have often been utilized to evaluate the vulnerability of buildings to overheating risks. Some authors argue that the WBGT index has suitable tolerance thresholds that should not be surpassed (Auliciems; Szokolay, 2007; Lamberts *et al.*, 2016). The SET temperature index has been adopted in various recent studies (Guarda; Mizgier; Hernandez, 2023), and considers the six parameters of thermal comfort: air temperature, radiant temperature, humidity, air velocity, metabolism, and clothing isolation.

Recently, the International Energy Agency in Buildings and Communities (IEA EBC) published the Annex 80 technical report, that outlines 37 recommendations for future international policies concerning energy efficiency and resilient cooling (IEA, 2023; Levinson *et al.*, 2023). The report aims to facilitate the implementation and integration of low-energy, low-carbon resilient cooling systems in buildings. Among the resilience indicators highlighted as key performance indicators (KPIs) for assessing thermal resilience, the report includes the IOD (Hamdy *et al.*, 2017), Exceedance Hours (HE) (CIBSE, 2013), Passive Habitability (PH) (Kesik; O'Brien; Ozkan, 2022), and Thermal Autonomy (TA) (Ko *et al.*, 2018). Additionally, the report mentions the LEED v4.1 certification pilot credit, "Passive Survivability" (USGBC, 2023), which incorporates SET, Heat Index, and WBGT indexes to evaluate thermal resilience.

In this context, Attia *et al.* (2023) discuss that, by the end of 2025, all European Member States utilizing the Energy Performance of Energy Directive (EPBD) will be required to review their national energy calculation methodologies and address discomfort concerns about climate change scenarios. The authors observed that some standards used for calculating overheating are being criticized due to their approach to calculate the thermal balance, which does not consider the estimation of comfort based on the six thermal comfort parameters.

## Adaptive thermal comfort Standard 55

Applying adaptive thermal comfort principles enables the assessment of thermal comfort within naturally ventilated buildings, as outlined in the methodology of Standard 55 (ASHRAE, 2017). Thermal comfort levels are defined by acceptable indoor operative temperature ranges ($T_o$, in °C), as determined from Equation 1 (upper limit) and Equation 2 (lower limit), using the 80% acceptability limits. The acceptable range is calculated based on the prevailing mean outdoor air temperature ($t_{pma(out)}$, in °C), which is a simple arithmetic mean of all of the mean daily outdoor air temperatures ($t_{mda(out)}$, in °C) over a period of no fewer than seven and no more than thirty sequential days. In this study, a mean of 10 days was used. The mean daily outdoor air temperature for every sequential ten days is calculated as the simple arithmetic mean of all outdoor dry-bulb temperature observations over a 24-hour period. Standard 55 (ASHRAE, 2017) is widely adopted in literature to assess overheating. Its application is valid when the prevailing mean outdoor air temperature falls between 10.0 °C and 33.5 °C. Concerning the climate of Cuiabá/MT, the $t_{pma(out)}$ for the current scenario is within this criterion and was calculated using the SWERA (Solar and Wind Energy Resource Assessment) climate file.

$$T_o = 0.31\ t_{pma(out)} + 21.3 \qquad \text{Eq. 1}$$

$$T_o = 0.31\ t_{pma(out)} + 14.3 \qquad \text{Eq. 2}$$

Where:

$T_o$ is the acceptable operative temperature (°C); and

$t_{pma(out)}$ is the prevailing mean outdoor air temperature (°C).

## Indoor Overheating Degree (IOD) and Exceedance Hours (HE)

The IOD metric (◦C) aims to quantify the risk of overheating by considering the intensity and frequency of overheating events in a building's internal environments by means of establishing distinct thermal comfort limits for different thermal zones. Intensity is quantified by the difference between the indoor operative temperature ($T_{fr,i,z}$) and the established comfort temperature ($TL_{comf,i,z}$), considering only positive differences. The frequency is calculated by integrating the overheating intensity during the occupancy period ($N_{occ}$) within the different thermal zones (z) to show the total overheating inside the building. The IOD was calculated using Equation 3 (Hamdy *et al.*, 2017):

$$\text{IOD} = \frac{\sum_{Z=1}^{Z}\sum_{i=1}^{N_{occ(z)}}[(T_{op,i,z} - TL_{comf,i,z})^{+}.t_{i,z}]}{\sum_{Z=1}^{Z}\sum_{i=1}^{N_{occ(z)}} t_{i,z}} \qquad \text{Eq. 3}$$

Where:

IOD is the indoor overheating degree (°C);

Z is the zone counter;

I is the occupied hour counter;

Z is the total building zones;

T is the time step (h);

$N_{occ}$ (z) is the total number of zonal occupied hours;

$T_{op,i,z}$ is the indoor operative temperature in zone z at time step i (°C); and

$TL_{comf,i,z}$ is the comfort limit temperature in time interval i in zone z (°C).

The adaptive thermal comfort range (ASHRAE, 2017) was adopted to calculate the IOD and HE metrics. Additionally, the HE metric was calculated, representing the percentage of occupied hours during which the operative temperature exceeds the defined comfort limit. This metric has been used in conjunction with the IOD index in several studies (Gamero-Salinas *et al.*, 2021; Gamero-Salinas; Monge-Barrio; Sánchez-Ostiz, 2020; Rahif *et al.*, 2021).

## Heat Index (HI)

The Heat Index (HI), proposed by Steadman (1979), represents the sensation of temperature for the human body when air temperature and relative humidity are combined. The HI temperature and its effects on human health are categorized in five levels: Safe, Caution, Extreme Caution, Danger, and Extreme Danger (Table 1). The adoption of this index to assess the thermal resilience of indoor environments can be seen in Flores-Larsen and Filippín (2021). According to Sun *et al.* (2021), this index can be applied to quantify extreme events.

The LEED v4.1, certification for sustainable buildings, developed by the USGBC (United States Green Building Council), recently incorporated the pilot credit named “Passive Survivability and Backup Energy during Disruptions” in the scope of its certification code (USGBC, 2023). This credit indicates thermal stress indices, such as the Heat Index and SET temperature, for assessing thermal safety and passive survivability. With this proposal, it is recommended that residential buildings have a maximum HI temperature of 32.2 °C (lower limit of the "Extreme Caution" category).

## Standard Effective Temperature (SET) and passive survivability

The SET index, developed by Gagge, Fobelets and Berglund (1986), is considered a comfort and heat stress metric. According to Standard 55, SET temperature corresponds to the temperature of an imaginary environment at 50% relative humidity, an average air velocity <0.1 m/s and an average radiant temperature equal to the average air temperature, in which the total heat loss from the skin of an imaginary occupant with an activity level of 1.0 met and clothing level of 0.6 clo is the same as that from a person in the real environment, with analogous clothing and activity level (ASHRAE, 2017).

The thermal sensation scale of the SET index and its corresponding effects on the body, detailed in Gagge, Fobelets and Berglund (1986), Auliciems and Szokolay (2007), Laouadi, Bartko and Lacasse (2021) and in Zheng *et al*. (2021), are shown in Table 2.

The SET temperature can be simulated using the software Energy Plus, which enables the evaluation of the percentage of hours (%) within each of the SET temperature ranges (°C) and their corresponding thermal sensation scales.

The LEED v4.1 certification for sustainable buildings determines the range between 12 °C SET and 30 °C SET as safe for habitability, and establishes a maximum threshold where the cumulative exposure above 30 °C SET should not exceed 120 °C.h, considering a 24-hour occupancy during the period of extreme heat indicated by the climate file (STAT) (USGBC, 2023). Therefore, following the LEED certification methodology, the accumulated value of °C SET-hours (°C.h) is calculated to assess the building's thermal safety and passive survival conditions.

Table 1 - **Heat Index (HI) temperatures and their levels/effects on human health**

| Heat Index (HI) [°C] | HI levels and effects on human health |
|---|---|
| < 26.7 °C | Safe: no risk of heat hazard |
| 26.7 – 32.2 °C | Caution: fatigue is possible with prolonged exposure and activity. Continuing activity could result in heat cramps. |
| 32.2 – 39.4 °C | Extreme caution: heat cramps and heat exhaustion are possible. Continuing activity could result in heat stroke. |
| 39.4 – 51.7 °C | Danger: heat cramps and heat exhaustion are likely; heat stroke is probable with continued activity. |
| > 51.7 °C | Extreme danger: heat stroke is imminent. |

**Source**: adapted from Tavakoli *et al*. (2022).

Table 2 - **Range of SET temperatures, and corresponding thermal sensation and physiology**

| SET (°C) | Thermal sensation | Thermal perception | Physiology |
|---|---|---|---|
| >37.5 | very hot | great discomfort | failure of evaporative regulation |
| 34.5 – 37.5 | hot | very unacceptable | profuse sweating |
| 30.0 – 34.5 | warm | uncomfortable, unacceptable | sweating |
| 25.6 – 30.0 | slightly warm | slightly unacceptable | slight sweat, vasodilation |
| 22.2 – 25.6 | comfortable | acceptable | physiological thermal neutrality |
| 17.5 – 22.2 | slightly cool | slightly unacceptable | initial vasoconstriction |
| 14.5 – 17.5 | cool | unacceptable | slow body cooling |
| 10.0 – 14.5 | cold | very unacceptable | beginning of shivering |

**Source**: adapted from Auliciems and Szokolay (2007).

# Method

## Building location, geographical and climatic boundaries

The residence chosen for investigation in this study is a single-family building designated for low-income occupants situated in the city of Cuiabá, Mato Grosso, in midwestern Brazil (Latitude 15°36′56″ S and Longitude 56°06′01″ W). The region features a Tropical Savannah climate (Aw) (Peel; Finlayson; McMahon, 2007), characterized by consistent high air temperatures, significant hydrothermal fluctuations throughout the year, and an undefined or absent winter season, factors leading to high hours of thermal discomfort inside buildings (Callejas *et al.*, 2019). The Tropical Savannah climate (Aw) covers 11.5% of the world's land area. It is found in 25.8% of Brazilian territory and, in represents 52.8% of the area in the state of Mato Grosso (Alvares *et al.*, 2013) (Figure 1).

Due to its geographical location, projections of future climate change scenarios and global socioeconomic development indicate an increase in the frequency of hot days in the tropics, impairing thermal comfort conditions. Consequently, existing buildings in these regions may be highly affected by the projected climate change. In these scenarios, the implementation of suitable bioclimatic strategies becomes crucial for adapting buildings to global warming, especially for the low-income population.

## Present and future climate change scenarios

Climate change scenarios were developed based on the morphing method using the current files in SWERA version and EPW (Energy Plus Weather File) extension, through WeatherShift tool (Dickinson; Brannon, 2016; Weathershift, 2023), adjusting current meteorological data to predicted climate changes from global circulation models and regional climate models. The tool provides future projection weather data for three time periods 2026-2045, 2056-2075, and 2080-2099 relative to the baseline period 1976-2005 – and two emission scenarios referred as Representative Concentration Pathways (RCPs) – RCP 8.5 and RCP 4.5 (Moazami; Carlucci; Geving, 2017). This methodology has been adopted in other recent overheating studies, such as in Gnecco *et al*. (2022).

Thus, following the methodology of the WeatherShift tool, the SWERA climate file in EPW format was used to assess the risk of overheating considering extreme maximum and minimum temperatures (Scheller *et al*., 2015). Unlike the TMY (Typical Meteorological Year) climate files, the SWERA file considers higher values of solar radiation and maximum temperatures (Scheller *et al*., 2015), enabling the evaluation of the overheating risk under extreme temperatures. The TMY files represent a year of average data, compiled from months across different years without extreme temperatures (Lamberts *et al*., 2016).

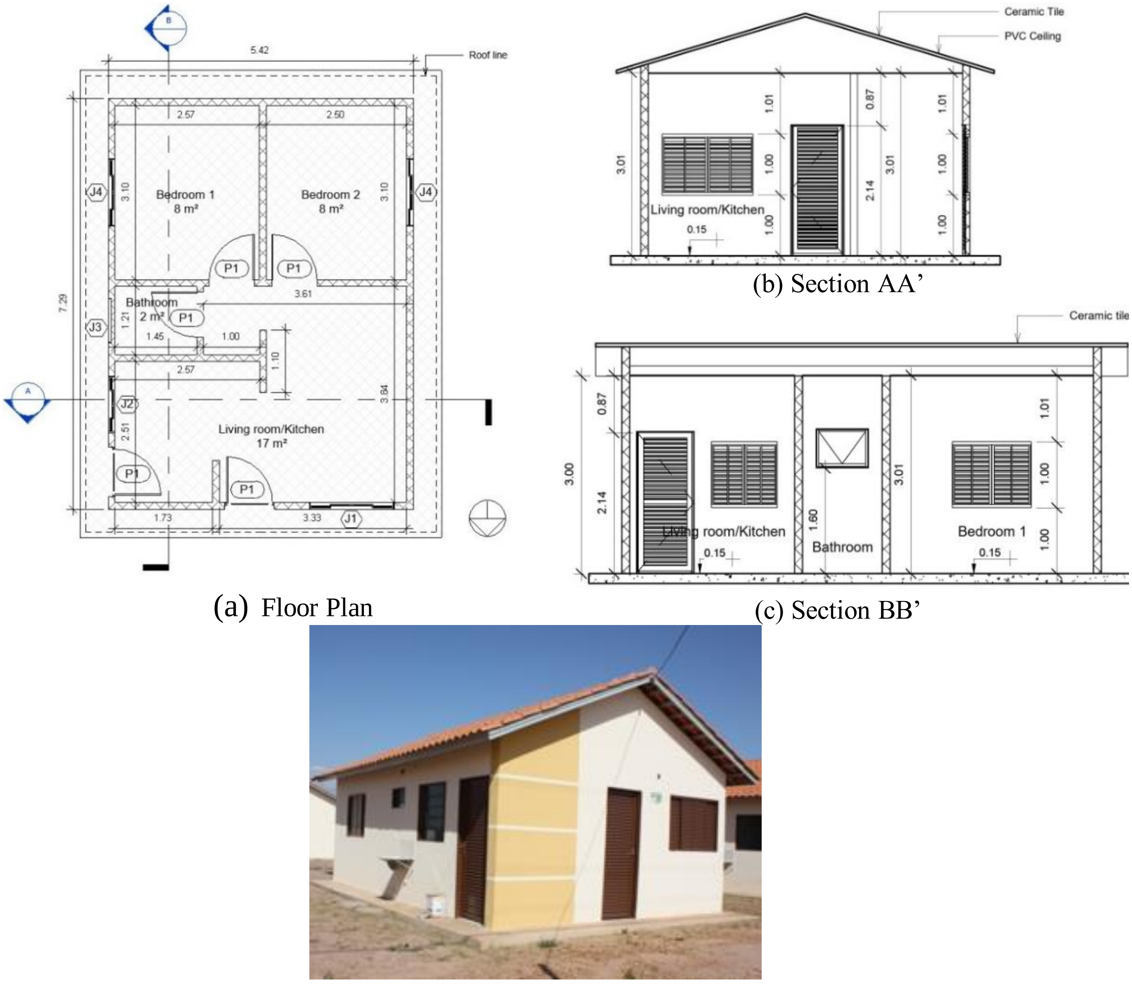
For the climate change scenarios, RCP 8.5 trajectories from the IPCC's Fifth Assessment Report (AR5) (IPCC, 2013) were adopted, representing higher greenhouse gas emissions due to continuous population growth, slow technological development, and fossil fuels dependence.

## Building simulation and computational models

The building evaluated in this study is a low-income single-family home (Figure 2). This typology was selected due to its extensive replication across all regions of Brazil as part of the MCMV social housing program by the Brazilian government (Caixa, 2024). The low-income population is the most vulnerable to high temperatures and climate change. This typology is distributed to occupants without consideration for climate adaptation, compromises their indoor thermal comfort conditions, and increases energy consumption for cooling (Guarda; Mizgier; Hernandez, 2023), resulting in poor thermal performance even in the current scenario, as discussed by Invidiata and Ghisi (2016) and Triana, Lamberts and Sassi (2018).

The computational model was developed based on the architectural project (Figure 2a) using Design Builder software v. 7.0.1.6 (DesignBuilder, 2024) and maintaining the same dimensions, geometry, and spatial distribution as presented in the project. Figures 2(b) and 2(c) illustrate sections of the building, while Figure 2d depicts an image of the constructed residential building. The building has a total area of 39.18 m², with 34.54 m² comprising the internal floor area, divided into four rooms: living room/kitchen (17.44 m²), bedroom 1 (7.78 m²), bedroom 2 (7.57 m²) and bathroom (1.75 m²). The roof is pitched with 0.30 meters of eaves. The ceiling height in the rooms is 3.00 meters. The living room and bedrooms have metal sliding windows, measuring 1.50 × 1.00 m and 1.20 × 1.00 m, respectively, consisting of two fixed single-glazed panels and two Venetian metal sliding panels. The kitchen window is a metal tilting window measuring 1.00 × 1.00 m.

Figure 2 – **Floor plan (a), sections (b) and (c), and exterior image (d)**




(a) Floor Plan

(b) Section AA'

(c) Section BB'

(d) External image of the low-income house

**Source**: adapted from Callejas *et al*. (2021).

## Characterizing the envelope of computational models

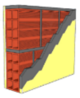
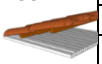
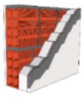
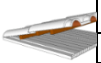
This study used two simulation models, with their characteristics detailed in Tables 3 and 4. The first model (HISp) represents standard housing. In HISp, the building materials used correspond to the existing, generally-used construction materials, employing properties estimated by NBR 15220 (ABNT, 2005).

The second model (HISe) incorporates passive bioclimatic strategies to enhance thermal performance. These strategies include using thermal insulation for the external walls (expanded polystyrene - EPS) and roof (aluminum thermal blanket). In addition, the absorptance of the external walls and roof was changed to a white color.

The modifications proposed for the envelope, which include thermal insulation and reduced absorption, are aligned with recommendations for the bioclimatic zone and tropical climate region. All other characteristics of the two models remain unaltered except for these adjustments related to the envelope materials.

Integrating these strategies into the building's design has resulted in a notable enhancement of thermal performance, allowing the building's envelope to attain a level 'A' on the Brazilian Energy Label for residential buildings (Callejas; Guarda; Durante, 2023). Images of the simulation model and its geometry are shown in Figure 3.

Table 3 - **Materials used in the HISp and HISe models and their thermal properties**

| Model | Envelope Element | Materials Layers of the element | Thickness [m] | Conductivity [W/m.K] | Specific Heat [J/kg.K] | Density [kg/m³] | U[1] [W/m²K] | α[2] | Thermal capacity [J/m²K] |
|---|---|---|---|---|---|---|---|---|---|
| Standard Housing (HISp) | External Walls  | Exterior Mortar | 0.025 | 1.15 | 1000 | 2000 | 2.49 | 0.60 | 150 |
| | | Ceramic brick | 0.09 | 0.90 | 920 | 1600 | | | |
| | | Interior Mortar | 0.025 | 1.15 | 1000 | 2000 | | | |
| | Floor | Concrete | 0.10 | 1.75 | 1000 | 2200 | 4.40 | 0.40 | 220 |
| | Roof  | Ceramic Tile | 0.01 | 1.05 | 920 | 2000 | 2.02 | 0.85 | 41.92 |
| | | Attic | >0.05 | - | - | - | | | |
| | | PVC Ceiling | 0.01 | 0.20 | 1340 | 1300 | | | |
| Housing with passive design strategies (HISe) | External Walls  | Mortar | 0.025 | 1.15 | 1000 | 2000 | 0.886 | 0.15 | 169.38 |
| | | EPS | 0.03 | 0.04 | 1400 | 15 | | | |
| | | Ceramic brick | 0.09 | 0.90 | 920 | 1600 | | | |
| | | Internal mortar | 0.025 | 1.15 | 1000 | 2000 | | | |
| | Floor | Concrete | 0.10 | 1.75 | 1000 | 2200 | 4.40 | 0.40 | 220 |
| | Roof  | Ceramic Tile | 0.01 | 0.65 | 840 | 1700 | 1.18 | 0.15 | 41.92 |
| | | Aluminum Blanket | - | - | - | - | | | |
| | | Attic | >0.05 | - | - | - | | | |
| | | PVC Ceiling | 0.01 | 0.20 | 1340 | 1300 | | | |

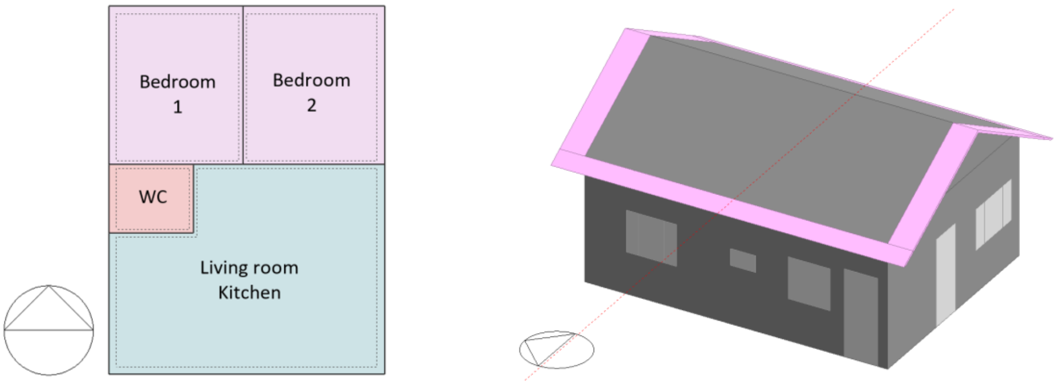
**Source**: adapted from Frota and Schiffer (2001), NBR 15220 (ABNT, 2005), and NBR 15575 (ABNT, 2021).
**Note:** [1] U: thermal transmittance; [2] α: absorptance (dimensionless).

Table 4 - **Thermal resistance of the materials and the unventilated air cavity**

| Material | Thermal Resistance [m².K/W] |
|---|---|
| Aluminum blanket | 0.67 |
| Air cavity with high emissivity surface, thickness >5.0 cm - downward flow 0.21 | 0.21 |
| Air cavity with high emissivity surface, thickness >5.0 cm - upward flow 0.14 | 0.14 |

**Source**: adapted from NBR 15220 (ABNT, 2005), and NBR 15575 (ABNT, 2021).

Figure 3 - **Schematic plan (a) and perspective view of the model (b)**




(a) (b)

**Source**: developed by the author using DesignBuilder software (DesignBuilder, 2024).

The windows have simple glazing with a Solar Heat Gain Coefficient (SHGC) of 0.87 and a thermal transmittance of 5.70 W/m².K. Both models used the same natural ventilation and infiltration parameters for doors and windows, following the NBR 15575 (ABNT, 2021) recommendations detailed in Table 5. The windows were set as opened during occupancy when indoor air temperature

(a) equaled or exceeded 19 °C; and

(b) was higher than the outdoor temperature.

When closed, the software considered the air infiltration parameters indicated in Table 5. Exterior doors in the living room/kitchen remained closed with infiltration throughout the year. Internal doors were set as opened, except the bathroom door, which was set as closed with air infiltration, as stated by the Brazilian standard.

Since soil temperature significantly influences the thermo-energy simulation, the Slab input tool was used to obtain the monthly soil temperature under the dwellings for both current and future scenarios, following the methodology adopted in some studies for the region (Callejas *et al.*, 2020, 2021). The soil temperature was derived using the “Finite Difference” model, with weather data defining boundary conditions. The manual developed by Mazzaferro, Melo and Lamberts (2015) was used as a reference for the GroundDomain input data.

### Occupancy, lighting and equipment

Occupancy and internal gains were taken from NBR 15575 (ABNT, 2021), specifying 2 people in the bedrooms and 4 people in the living room, with a metabolic activity of 81W/person in the bedrooms and 108W/person in the living room/kitchen. A lighting power density of 5.0W/m² was considered in all rooms. The bedrooms are occupied from midnight to 8 am, and the living room/kitchen from 2 pm to 10 pm, covering both weekdays and weekends. In the living room/kitchen, the equipment's power density was set to 6.0W/m² during occupancy hours. The building was considered naturally ventilated, following the simulation parameters presented by standard NBR 15575 (ABNT, 2021).

# Results and discussions

The following sections present the simulations and calculations results for one year of operation in naturally ventilated mode. Simulations were conducted for two dwellings, the standard dwelling (HISp) and the dwelling incorporating passive design strategies (HISe). The results were calculated and compiled based on four groups of metrics:

(a) adaptive thermal comfort (ASHRAE, 2017);

(b) Indoor Overheating Degree (IOD) and Exceedance hours (HE);

(c) Heat Index (HI); and

(d) Standard Effective Temperature (SET) and Passive survivability based on LEED certification methodology.

## Adaptive thermal comfort ASHRAE 55

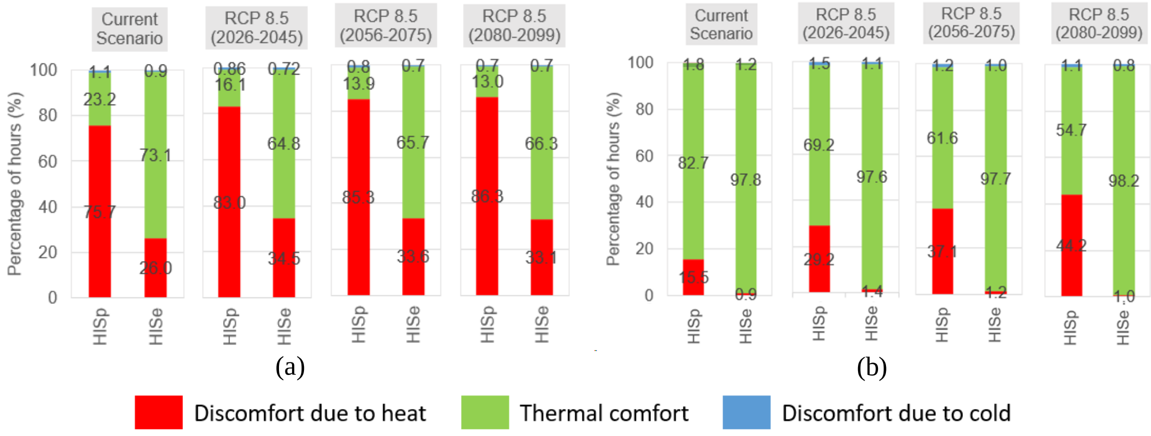
Figure 4 illustrates the hours of comfort and discomfort due to cold and heat in the living room/kitchen and bedrooms of the HISp and HISe dwellings. In HISp, bedrooms maintain 83% annual thermal comfort from midnight to 8 am, while the living room/kitchen only achieves 23% comfort from 2 pm to 10 pm. With passive measures in HISe, heat discomfort hours in bedrooms reduced by 14.6%, and in the living room/kitchen by 49%.

Table 5 – **Natural ventilation and infiltration parameters for doors and windows**

| Parameters | Doors | Windows |
|---|---|---|
| Air mass Flow Coefficient when Opening is closed [kg/(s.m)] | 0.0024 | 0.00063 |
| Air mass Flow Exponent when Opening is closed (dimensionless) | 0.59 | 0.63 |
| Discharge Coefficient for Opening Factor (dimensionless) | 0.60 | 0.60 |

**Source**: adapted from NBR 15575 (ABNT, 2021).

Figure 4 - **Adaptive thermal comfort results of the kitchen/living room (a) and bedrooms (b) in current and climate change scenarios**




In future climate change scenarios, there is a gradual decrease in the annual hours of comfort, particularly in HISp dwelling. When compared, HISe outperforms HISp in all scenarios, showing passive design measures effectively reduced the vulnerability of occupants to overheating risk and enhanced the building's habitability.

The reduction in discomfort hours within HISe dwelling in future scenarios is noteworthy. In HISe, indoor operative temperatures rise proportionally less than outdoor temperatures and thermal comfort limits. This result may be attributed to the substantial reduction in maximum temperatures resulting from the implementation of passive measures, alongside the adaptive methodology outlined in Standard 55 (ASHRAE, 2017), which allows for higher comfort ranges across future scenarios. This outcome raises questions about the index's suitability for overheating analysis in future scenarios of tropical climates, considering the high temperatures predicted.

## Indoor overheating degree and exceedance hours

The IOD (°C) and HE (%) metrics were calculated for the HISp and HISe dwellings for current and future climate scenarios, considering the Adaptive thermal comfort limits and 80% acceptability interval (Table 6) (ASHRAE, 2017). The IOD values correspond to the degree of indoor overheating, indicating the sum of the positive values resulting from the difference between the indoor operative temperature (To) and the established thermal comfort limit.

According to the results presented in Table 6, it is noted that both IOD and HE values increased across future scenarios in HISp dwelling. When comparing the performance of HISp and HISe in the current scenario, the results demonstrate the effectiveness of the passive strategies implemented in HISe, resulting in a substantial reduction of 75% in HE and 93% in IOD value, corresponding to a difference of 0.5242 °C. In future scenarios, the reductions reach 82% in HE and 95% in IOD value, corresponding to a difference of 1.0644 °C, under RCP 8.5 (2080-2099).

The passive strategies implemented in HISe reduced occupants' vulnerability to overheating risks, as evidenced by the decrease in indoor overheating degree and exceedance hours across all evaluated scenarios compared to HISp. IOD and HE calculations were based on the adaptive thermal comfort methodology (ASHRAE, 2017) and as discussed in previous section, the reduction of these values in future scenarios within HISe dwelling is noteworthy. Despite the outlined considerations, the IOD and HE metrics effectively identified which dwelling had a higher potential for mitigating overheating risk while showing the degree of overheating (°C) in each case.

## Heat Index (HI)

The distribution of the occurrence of HI temperatures in the standard dwelling (HISp) and the dwelling (HISe) are shown in Figures 5 (HISp) and 6 (HISe).

Table 6 - **IOD and HE results**

| Scenarios | Current | | RCP 8.5 (2026-2045) | | RCP 8.5 (2056-2075) | | RCP 8.5 (2080-2099) | |
|---|---|---|---|---|---|---|---|---|
| **Metrics** | **HISp** | **HISe** | **HISp** | **HISe** | **HISp** | **HISe** | **HISp** | **HISe** |
| HE (%) | 32.2 | 8.1 | 44.1 | 10.8 | 50.6 | 10.4 | 56.0 | 10.1 |
| IOD (°C) | 0.5613 | 0.0371 | 0.8416 | 0.0547 | 0.9716 | 0.0511 | 1.1142 | 0.0498 |

Figure 5 - **Distribution of the occurrence of HI temperatures (% of hours) and corresponding thermal classification within the HISp dwelling**

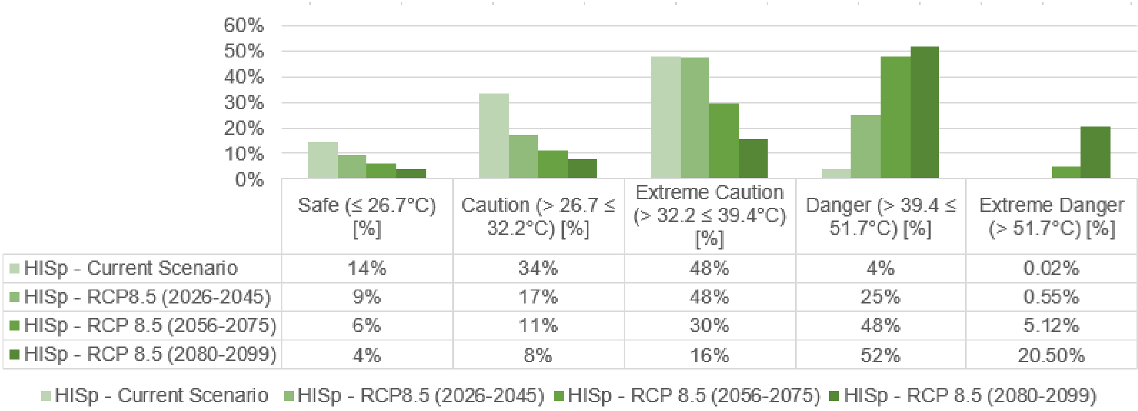
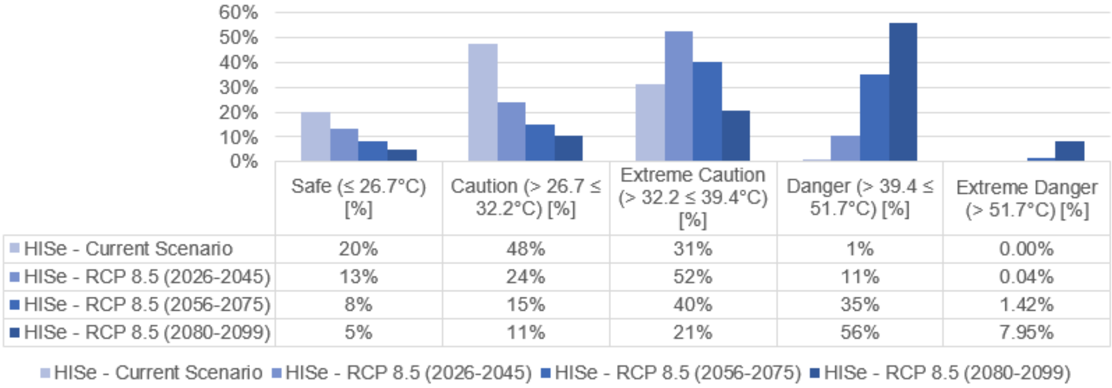



Figure 6 - **Distribution of the occurrence of HI temperatures (% of hours) and corresponding thermal classification within the HISe dwelling**




Regarding the current scenario, the results present that, in HISp dwelling, HI temperatures are classified as "Extreme Caution" in 48% of the hours, 4% as "Danger" classification (39.4 and 51.7 °C), and 0.02% as "Extreme Danger" (> 51.7 °C). When evaluating future scenarios, there is an increase in the number of hours in the "Danger" classification, which corresponds to most occurrences in the RCP 8.5 scenarios (2056-2075 and 2080-2099), and in "Extreme Danger" range, which accounts for 20% of hours in the RCP 8.5 scenario (2080-2099).

Concerning the HISe dwelling (Figure 6), the highest occurrence of hours in the current scenario is classified within the "Caution" interval (48%). There are 31% of hours in the "Extreme Caution" range (-17% compared to HISp), 1% in "Danger" (-3% compared to HISp), and no occurrences in the "Extreme Danger" range. In future scenarios, there is an increase in hours in the "Extreme Caution" classification, which becomes the majority of occurrences in the RCP 8.5 scenarios except for the 2080-2099 period, where the highest occurrence of hours is in the "Danger" interval (56%).

When comparing the performance of HISp and HISe dwellings, it is noticed that the passive strategies increased the occurrences of temperatures in the "Safe" and "Caution" categories and reduced the hours in the "Danger" and "Extreme Danger" classifications, reducing the occupants' vulnerability and improving the indoor environmental quality of the HISe dwelling.

Despite reductions in occurrences in the "Danger" and "Extreme Danger" ranges, both in present and future climate change scenarios, and improvements in habitability conditions, it is evident that the values obtained in HISe still do not meet the LEED certification requirement, which is 32.2°C (upper limit of the "Caution" level). Even in the present scenario, there are HI temperatures higher than the recommended value in both dwellings, indicating overheating risk due to high temperatures in the tropical savannah climate. Thus, considering the HI temperature of the certification as a reference, neither of the dwellings provides adequate thermal comfort conditions for the occupants.

## Standard Effective Temperature (SET) and passive survivability

The percentages of hours (%) within each SET temperature interval/scale were computed, allowing for the identification of thermal and comfort sensations experienced by occupants in the bedrooms and living room/kitchen of both the HISp and HISe dwellings in the present and future RCP 8.5 scenarios (2026-2045, 2056-2075, 2080-2099) (Figure 7).

In the current scenario, the SET temperatures within the bedrooms are only 16% (HISp) and 24% (HISe) of the occupied hours in the “comfortable and acceptable” classification. Even in the present scenario, occupants are "slightly warm, slightly dissatisfied" most of the time (69% of occupied hours) in both dwellings. In the living room/kitchen, the occupants are thermally neutral and comfortable in only 5% (HISp) and 9% (HISe) of the occupied hours.

It can be seen that, even in the present scenario, the occupants of the living room/kitchen in the HISp dwelling are in the "warm, uncomfortable" range most of the time (67%), followed by the "slightly warm, slightly dissatisfied" range (23%).

In (HISp), the SET temperatures are most of the time (52%) in the "slightly warm" range, followed by 37% of the time in the "warm, uncomfortable" range. However, despite the decrease in SET temperatures and the reduction in the number of hours in the most thermally uncomfortable intervals (>30 °C), the estimated temperatures are still very high, which is alarming, as also analyzed and mentioned by Guarda, Mizgier, and Hernandez (2023, p. 9). An increase in the percentage of hours classified as “hot, very unacceptable” and “very hot, great discomfort” categories was observed in the RCP 8.5 scenario (2026-2045).

The Figure 8 shows the degree-hours (°C SET-hours) calculated for the living room/kitchen and bedroom of the HISp and HISe dwellings, in the present scenario and future RCP 8.5 projections, during the period of extreme heat (which corresponds to the 10th and 16th of October). The assessment considers 24 hours of occupancy, according to the LEED certification methodology (USGBC, 2023).

Regarding passive survivability, as evaluated by the LEED certification methodology, it can be seen that most of the time, the SET temperatures simulated are higher than the thermal safety temperature of 30 °C SET, defined by LEED certification (USGBC, 2023) as the "habitable temperature" limit.

Figure 7 - **Percentage of hours (%) in each SET temperature range and corresponding thermal sensation, simulated for the kitchen/living room (a) and bedrooms (b) in HISp and HISe models**

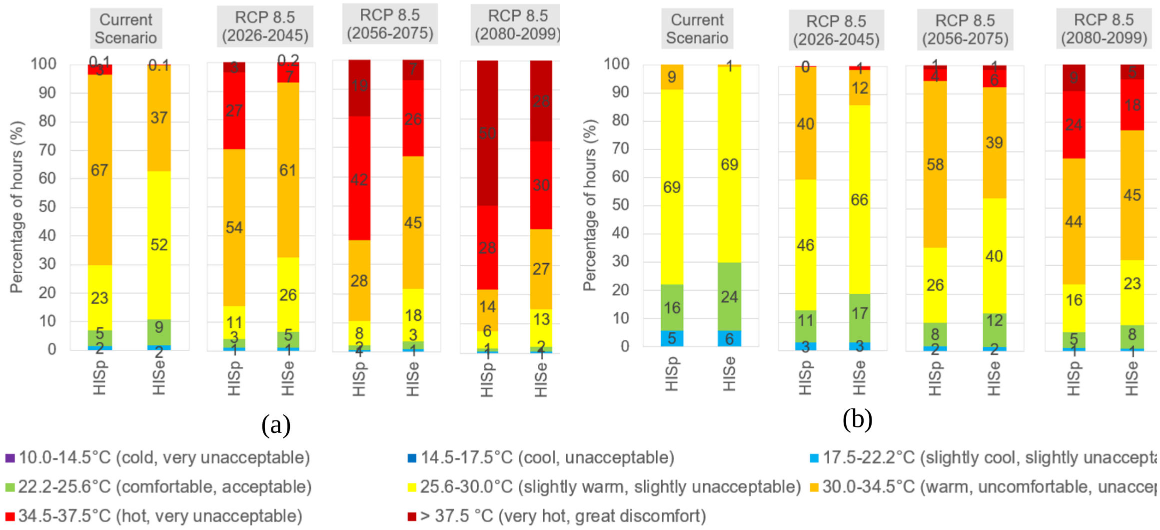
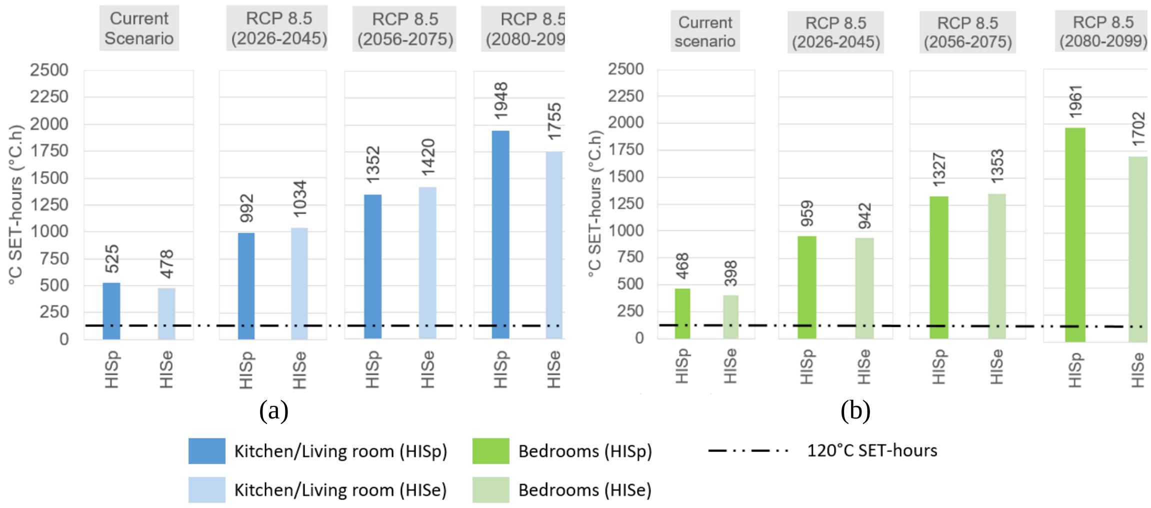


Figure 8 - **Degree-hours (°C SET-hours) above 30°C SET, estimated for kitchen/living room (a) and bedrooms (b) of the dwellings HISp and HISe in present and climate change scenarios**




A gradual increase in °C SET-hours across the future climate scenarios, when compared to the current one, is noticeable. Concerning the passive strategies adopted in the HISe, they promoted a reduction in the occurrence of °C SET-hours above 30 °C SET in all climate scenarios evaluated. In the present scenario, the strategies implemented led to a reduction of 47 °C SET-hours in the living room/kitchen (9%) and 67 °C SET-hours in the bedrooms during the period of extreme heat (15%).

Despite the significant reduction in °C SET-hours, providing fewer hours of discomfort and thermal stress for the occupants, the values in HISe do not meet LEED certification, as they exceed 120 °C SET-hours, indicating that none of the dwellings provides thermal safety and passive survival conditions for the tropical savannah climate. It is worth emphasizing that the proposed limit does not seem to be suitable for the tropical savannah climate region, most probably because it was defined based on other types of climates that are less severe in terms of heat and should be used with caution and explored in new case studies in tropical climates.

## Discussion

The adaptive thermal comfort and the IOD metric utilize a thermal balance approach, analyzing the heat balance between indoor and outdoor environments. In contrast, SET-based indices prioritize thermal comfort and occupants' well-being, considering comfort variables like air temperature, radiant temperature, humidity, air velocity, metabolism, and clothing (Attia *et al.*, 2023; Rahif; Amaripadath; Attia, 2022).

In the case of the IOD metric, the methodology's strength lies in its multi-zone approach, which is sensitive to climate change in its quantification of the overheating risk and resistance of cooling strategies. It is worth noting that this methodology allows the adoption of various thermal comfort limits, such as fixed/static or adaptive, varying in each building's thermal zone, and enabling the selection of the most suitable range per zone.

The IOD values calculated for the HISp and HISe dwellings in this study are of the same order of magnitude as those found in literature (Flores-Larsen; Filippín; Bre, 2023; Gamero-Salinas *et al*., 2021; Rahif *et al*., 2021, 2022), corroborating with the results presented.

Regarding the method limitations, the absence of a reference parameter for acceptable IOD values complicates the interpretation and validation of the results. Although the IOD provides an average of overheating intensity across all occupied zones, as highlighted by (Laouadi; Bartko; Lacasse, 2020), it lacks threshold values to indicate when overheating limits are exceeded. When comparing various strategies or climate scenarios, variations in IOD can be seen, helping to interpret the impact of the variables on the building's performance. Another notable limitation is that the methodology focuses exclusively on temperature. Future research suggestions include incorporating additional comfort parameters such as humidity, metabolic rate, air velocity, and clothing, as proposed by Rahif, Amaripadath, and Attia (2021) and Rahif *et al.* (2021) and Flores-Larsen, Filippín and Bre (2023).

Aligned with this approach, recent studies recommend the use of SET, which considers all six thermal comfort parameters. It is important to note that the indices based on operative temperature are adapted to the climate scenario evaluated, while SET-based indices are not. The maximum recommended SET temperature value by LEED certification for residential buildings (USGBC, 2023) is 30 °C-SET, corresponding to a "warm" and "slightly uncomfortable" sensation, being adopted by Guarda, Mizgier, and Hernandez (2023) to assess the severity and intensity of overheating events in tropical climate. The high percentage of hours within 30.0-34.5 °C ("slightly uncomfortable") in the current scenario could suggest that the occupants have adapted to higher SET temperatures in this climatic context, an issue already addressed in Borges, Callejas and Durante (2020), Guarda (2023) and Guarda, Mizgier and Hernandez, 2023 that also considered the savannah tropical climate.

In addition, the LEED certification recommends a maximum of 120 °C-SET-hours for an extreme heat period with temperatures exceeding 30 °C-SET. However, this proved to be very restrictive, as temperatures above 35 °C-SET were observed throughout the year even in the current climatic scenario. Nonetheless, this threshold appears to be appropriate for studies conducted in other climates (Laouadi *et al*., 2020, 2023; Laouadi; Bartko; Lacasse, 2020).

Regarding the tropical savannah climate, overheating cannot be evaluated exclusively during the summer period, or during the week of extreme heat since overheating events occur throughout the entire year. It is worth highlighting that the occupancy period impacts indoor performance, as areas of the building predominantly occupied during the day (living room/kitchen) showed more discomfort hours than those predominantly occupied at night (bedrooms) (Guarda, 2023). However, if a 24-hour occupancy is considered, as required for LEED evaluation, the indoor performance is similar, indicating that the main difference lies only in the occupancy time considered.

It is important to note some potential limitations. For example, only one case study is evaluated, focusing on the results obtained for the tropical savanna climate, while excluding other climates. Although overheating has been extensively evaluated, the use of indices in tropical climates still requires further exploration. For example, it would be interesting to conduct on-site research to compare measured heat stress levels with simulation results, especially concerning SET and HI temperatures, which could contribute to identifying adaptive parameters to tropical regions. Findings of an on-site investigation could be used to define more precise parameters that, in turn, could be used to assess the intensity and severity of the overheating in the region. Finally, regarding the weather files adopted, it would be interesting to consider more recent climate files in future studies to capture the effects of heatwaves as they are occurring more frequently in the region (Silva *et al.*, 2022).

# Conclusions

This study evaluated the thermal resilience of two low-income naturally ventilated models in overheating situations located in the tropical savannah climate region. A standard dwelling (HISp) and a dwelling incorporating bioclimatic passive design strategies (HISe), such as insulation and low absorption, were simulated considering current and future climate change scenarios. These strategies can be applied either during the design phase or through renovations to existing dwellings. The overheating analysis considered the adaptive thermal comfort, Heat Index (HI), IOD and HE, and SET temperature indexes.

The HISp dwelling displayed inadequate thermal comfort conditions, characterized by high levels of heat discomfort, especially noticeable in the kitchen/living room, even in the current scenario. Heat Index (HI) calculations show temperatures in "Extreme Caution", "Danger" and “Extreme Danger” categories, which get progressively more severe in future scenarios.

Incorporating bioclimatic passive design strategies in the HISe dwelling reduced discomfort hours, overheating risk, and heat stress levels in tropical savannah climate regions, as verified through the adoption of various indices. Despite the reduction in occupants’ vulnerability to the overheating risk and the improvement in the habitability of the HISe dwelling, HI temperatures still exceeded the "Caution" level. Regarding the SET temperature, several hours were in the “Warm, uncomfortable” category, surpassing 120 °C SET-hours with temperatures above 30 °C SET even in the current scenario, with an increase in future scenarios. It is worth noting that the limits of habitable temperature for HI and SET, established by LEED certification, proved to be stringent for the tropical savannah climate.

Comparing the performance of both dwellings, the HISe demonstrated greater thermal resilience and capacity to adapt to high external temperatures, resulting in fewer hours of overheating, discomfort, and thermal stress in current and climate change scenarios. However, despite the reduction of the overheating intensity and severity in the HISe dwelling, it is noted that none of these typologies offers conditions for thermal safety and passive survivability in the tropical savannah climate. High temperatures and overheating events are present throughout the year, resulting in a significant occurrence of thermal stress. This phenomenon is present even in the HISe, which remains vulnerable to overheating risk, despite being classified as level A in energy efficiency by the Brazilian Energy Label for residential buildings (INI-R).

Current standards and performance codes do not incorporate climate change projections, despite housing having a lifespan of approximately 50 years. Therefore, ensuring that homes built today achieve an initial “A” rating for envelope performance is essential to mitigate the severity and intensity of overheating risks in the current and future scenarios.

Future studies should consider establishing requirements and parameters for overheating risk in buildings, including minimum, critical, and maximum acceptable limits for social housing, bearing in mind the occupants' vulnerability to overheating risks in the savannah tropical climate.

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